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ORIGINAL ARTICLE

Geological aspects of decomposition of corpses in mass graves from WW1 and 2, located in SE Poland

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Abstract The investigations were carried out to identify processes and mineral products in the diversified subsoil sediments of mass graves from WW1 (four graves) and 2 (five graves) and their surroundings, as well as the relations between the development of sediments within the mass graves and the scale of migration of the products of corpse decomposition. The author studied the role of iron compounds and clay minerals in the decomposition of human corpses buried in mass graves, followed by the migration of selected elements. In particular, he concentrated on the list of elements found in the diversified sediments of nine mass graves from SE Poland and to their relationship with phosphorus compounds. The methods applied included scanning electron microscopy (SEM) and optical polarizing microscopy. Samples were collected from various depths in trenches and holes dug in the vicinity of the graves, the sediments from the burial horizon and, when possible, the sediments underlying the grave (studied downslope). Detected phosphorus occurs as a weakly crystalline compound in silt-rich sediments with relatively stable water conditions. In silt-rich sediments with relatively stable moisture content, phosphorus occurs as a weakly crystalline compound. More stable aggregates of decomposition products have been found on quartz grains covered with clay-ferruginous rims. Fragments of human soft tissue were found only in those graves from WW2. There is no link between the spectrum of elements in the sediments of the graves and the period of burials. The decomposition products that form depend primarily on the type of sediments in which the mass graves were dug and, secondarily, although related, on the moisture content of the sediments. It has been found that stabilization of decomposition products in situ is related to the presence of iron compounds and clay minerals, particularly in finer-grained, aleuritic–pelitic sediments.

Keywords Mass graves · Decomposition · Clay minerals · Iron · Mineralogical

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Introduction

Most of the investigations related to the problem of burials focus on determining such components as ion content in the saturation and aeration zones ((Pacheco et al. 1991; Knight and Dent 1995), enteric bacteria (Dent and Knight 1998; Matos 2001), amino acids (Żychowski et al. 2002) and organic compounds (Żychowski 2006; Spongberg and Becks 2000a) in groundwater, adipocere (Forbes et al. 2004) and elements present in the subsoil (Spongberg and Becks 2000b; Mączyńska et al. 2006). Bones of the buried are another subject of investigation. As time goes by, bones lose calcium and phosphorus, the two major components, and undergo mineral alterations. For instance, bone may be mineralized by chemical compounds occurring in the vicinity of the burial site: silicon dioxide–amorphous silica to quartz, oxyhydroxides of iron and manganese, or even calcium carbonate–calcite (Pawlikowski et al. 2007). Organic acids formed during the decomposition of corpses dissolve the silicate minerals of the grave-containing sediments with simultaneous formation of phosphoric acid. For this reason, newly formed minerals, e.g., microcrystals of secondary quartz, may accompany crystallization of phosphorus-containing compounds. Simultaneously, the fibrous structure of the bone collagen disappears and is replaced by shred-like, irregular organic forms (Pawlikowski et al. 2007). Such processes are proof of the chemical alterations that take place within archeological sites (Pawlikowski et al. 2000). Studies on decomposition mechanisms are only in their initial stages. For instance, the decomposition of starch grains in soils (Haslam 2004) provides end products, which may be used in the identification of both damaging and preserving factors of the process.

Elements contained in decomposition products also make it possible to identify the material that has decomposed (Trąbka 2003) or the places of specific ceremonies or handicraft activities (e.g., painting (Parnell et al. 2002). Higgins and Burns (1975) suggest the connection of P with Fe, Ca, Mg and Al during the decomposition process of corpses. Also, other scientists have confirmed these results (Dent et al. 2004).

My studies have to either prove or disprove the idea that new compounds could be formed out of decomposition products and the components of the natural environment. The emergence of such new compounds and the condition of human corpses were documented by photographs of microscopic images under suitable magnifications of up to 60 and 120 times. Because of cultural concerns, the ground samples were collected primarily from the vicinity of graves. Wherever the owner of the land consented, boreholes were drilled to collect samples. The material subject to analysis did not concern the superficial layer of the substrate. The ground at the sampling sites was dug and subjected to serious deformation.

The aim of the investigations

Investigations were carried out to identify processes and mineral products (P-bearing ones, Fe compounds and clay minerals) in diversified subsoil sediments of nine mass graves and their surroundings, as well as the relations between the development of sediments within the mass graves and the scale of migration of the products of corpse decomposition. Determining the state of preservation of the decomposition products in the mass graves from World War 1 and 2 was an additional aim of the research. The investigation concentrated also on the secondary minerals and their types formed during corpse decomposition. Bone microfragments found in sediments adjacent to the graves (none of the graves was directly penetrated) were also studied with a focus on their alterations.

Methods

Samples were collected from various depths in vertical profiles of nine mass graves or in their immediate vicinity, and represented the sediments overlaying the grave, the sediments from the burial horizon and, when possible, the sediments underlying the grave (studied downslope). The sampling sites were selected considering the development of the mass grave sediments.

Samples from five sites (graves and their surroundings) were collected in such a way that the rock texture was preserved. After digging a pit of about 2-m deep, small horizontal openings were made and a plastic box sampler 4 cm high was carefully inserted upward into the roof of each opening. The following sites were sampled while applying this method:

- Bochnia, below of a grave from WW1, on the slope, in a line of graves; depths: 0.40–0.44 m, 0.62–0.66 m, 1.38–1.42 m and 1.6–1.64 m;
- Niepołomice, 8 m to the west of a grave from WW2; depths: 0.3–0.34 m, 0.66–0.70 m, 1.22–1.26 m and 1.88–1.92 m;
- Dukla, on a gentle slope, 4 m down from a mass grave from WW2; depths: 0.56–0.60 m, 0.74–0.78 m and 1.64–1.68 m;
- Barwinek, 2 m down from a mass grave from WW2, situated on a gentle slope; depths: 0.26–0.30 m, 0.86–0.90 m and 1.30–1.34 m;
- Nowy Sącz, at a Jewish cemetery, close to buildings, near a mass grave from WW2; depths: 0.36–0.40 m, 0.86–0.90 m and 1.26–1.30 m.

Therefore, a total of 17 samples were collected from these sites. The depth of the sample collection resulted from differences in vertical profiles. The respective owners of land where the graves were situated gave permissions to dig near some graves.

Additional samples were also taken from other mass graves to collect material from those horizons of the profiles, where the sediments showed definite changes of color, in comparison with the color dominating the profile. It was deemed that the coloration in the ground was indicative of the presence of studied compounds, i.e. iron compounds, and that these components differentiated the sampled sediments. The presence of decomposition products was also expected in this material. Materials of this type were taken from mass graves from WW2 in Niepołomice, Zbylitowska Góra, Dukla and Barwinek and from a mass grave from WW1 in Błonie. Additional samples were collected, depending on the type of sediments, using an auger drill with a sampler. This manner of collecting 14 samples was applied to graves on land where the landowners consented to drilling. The samples were obtained from mass graves from WW2 in:

- Niepołomice, at depths 0.5 m, 1.1 m and 1.3 m;
- Zbylitowska Góra, at depths 0.5 m and 1.2 m;

and mass graves from WW1 in:

- Rajbrot, at depths 0.6 m, 1.6 m and 2.2 m;
- Błonie, at depths 0.6 m, 1.0 m and 1.6 m;
- Brzesko, at depths 0.5 m, 1.4 m and 1.9 m.

The material collected was dried and hardened in an epoxy resin. Next, standard thin sections were cut with a diamond saw and polished. Mineralogical and petrographical observations were carried out with the use of optical polarizing microscopes (universal Olympus BX-51 and Polmi A, the latter with an attachment for taking photomicrographs at magnifications of up to 120×). The latter microscope was also used in observations of grain mounts applying side illumination (magnifications up to 60×). Using a digital, computer-controlled camera Olympus DP-12 with the analysis program and equipped with a CCD sensor with a resolution of 3.34 MP, the author observed mineralized zones of sediments at magnifications of up to 30×.

Observations were also made on samples covered with carbon using a scanning electron microscope (JEOL 5200).

Characteristics of sampling sites

Mineralogical and petrographical observations of sediments were made on samples collected from nine mass graves dating back to World Wars 1 and 2 (Fig. 1). It has been assessed that between 310 and 10,000 people (Table 1) had been buried without coffins in graves. The sites studied were situated in various physical–geographical units (Table 2). These sites were selected to take into account different substrates of extreme permeability. Both sandy and loamy sediments were included, so that difficulties associated with the determination of diversity of permeability of the substrate with depth were avoided. The fluctuations in the water table levels were established based on the observation of the area and interviews with local residents. Those located within the Sandomierz Basin include: a Pleistocene sandy terrace of the Vistula River in Niepołomice; an escarpment of a high, Pleistocene gravel

Table 1 Characteristics of the burials

Location	Number of people buried	Approximate size of the grave (m)
Barwinek	500	5 × 26
Błonie	312	30 × 100
Bochnia	417	30 × 22
Brzesko	507	70 × 45
Dukla	10,000	30 × 40
Niepołomice	700	20 × 10
Nowy Sącz	400	10 × 20
Rajbrot	530	60 × 30
Zbylitowska Góra	10,000	50 × 100

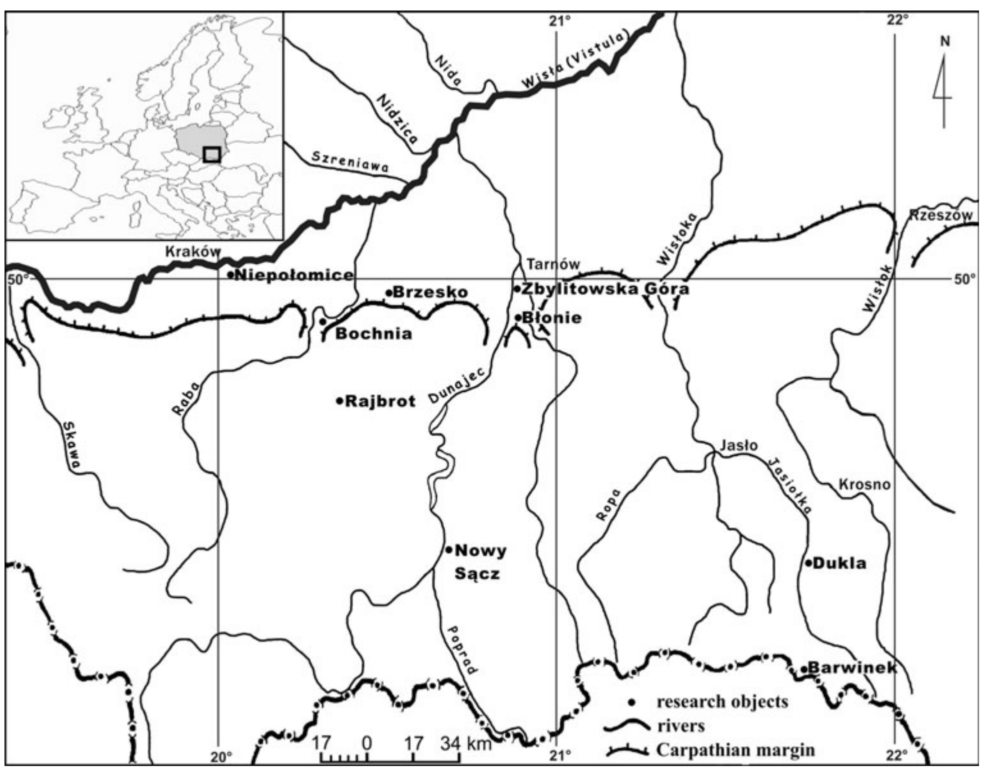

Fig. 1 Location of the mass graves studied in SE Poland

Table 2 Characteristics of the mass grave sites: geographical location, landforms, subsoil, land use

Locality, time of burial	Geographical unit	Landform; type and permeability of subsoil	Land use in the vicinity of mass graves
Niepołomice, WW2	Sandomierz Basin	Pleistocene sandy terrace underlain by Miocene clays; high permeability, variable water table	Pine–birch forest
Zbylitowska Góra, WW2	Sandomierz Basin	Front of the landslide escarpment of the high Dunajec River terrace; fine gravels with larger pebbles, overlain by silty sediments; diversified permeability	Mixed forest (beech, pine, oak)
Brzesko, WW1	Sandomierz Basin (Szczepanowska elevation)	Upper part of a slope gently inclined to the SW; sandy sediments; high permeability	Jewish cemetery, allotment gardens
Bochnia, WW1	Bochnia Foreland	Lower part of a gently inclined slope; diversified clays, loams; low permeability	Graves of the parish cemetery
Błonie, WW1	Ciężkowice Foreland	Upper part of a gently inclined slope of the foreland escarpment; sands and gravels; high permeability	Mixed forest, arable land to W on the other side of the road
Rajbrot, WW1	Wiśnicz Foothills	Elevated plateau; sandy mantle rock with fragments of flysch sandstones; high permeability	Beech–birch forest, arable land
Dukla, WW2	Jasło Foothills	Middle part of a gently inclined slope; clays overlain by loams; low permeability	Meadow next to a grave from WW1, cemetery uphill on the other side of the road
Barwinek, WW2	Beskid Niski Mts	Flattened area in the lower part of the gently inclined slope; loams; low permeability	Spruce forest
Nowy Sącz, WW2	Sądecka Basin	Agriculture terrace by the Kamienica and Dunajec rivers; silty sediments within the burial part; diversified permeability	Mass grave on a pre-war Jewish cemetery

terrace of the Dunajec River in Zbylitowska Góra modeled by a landslide; and a sandy, slightly inclined top surface of the Szczepanów elevation in Brzesko.

The foreland of the Carpathians was represented by two sites with mass graves from WW1, i.e., Błonie near Tarnów and the cemetery (with mass grave from WW1) in Bochnia. The grave in Błonie lies in the upper part of a gently inclined slope of the foreland escarpment. The other mass grave (Bochnia site) is situated in the upper part of the loamy front of the foreland escarpment with an inclination of 6–8% and surrounded by graves from a parish cemetery.

The Carpathian Foothills is represented by two mass graves: of soldiers of WW1 in Rajbrot (Wiśnicz Foothill) and WW2 Soviet soldiers from the period of the Dukla Pass battle in 1945 (Jasło Foothill). The grave in Rajbrot is situated at an elevation, at the woodland border and dug in a sandy ground with an admixture of larger fragments of flysch sandstones from the Silesian unit of the Carpathians. The grave in Dukla lies in the middle part of a gently inclined slope, and dug in loams and clays close to other graves from WW1 and of a parish cemetery. The geographical environment of low mountains is represented by a mass grave of civilians, dug in loams and clays in Barwinek in the Low Beskid Mountains. The grave lies on a forested, flattened area in the lower part of the gently inclined slope. Investigations were also carried out in the Sądecka Basin at a cemetery containing a mass burial from the period of WW2. The site is situated on an arable, silty terrace close to the confluence of the Kamienica River and the Dunajec River in Nowy Sącz.

Two mass graves from WW1 are adjacent to other burial places: a parish cemetery in Bochnia and Jewish cemetery in Brzesko. The other two were dug outside official burial areas: in the woodland border in Rajbrot and in Błonie. Three other mass graves from WW2 were situated in woodlands outside cemeteries in Niepołomice, Zbylitowska Góra and Barwinek, whereas two others—in Nowy Sącz and Dukla—were situated close to other graves. Trees were planted after digging the latter two mass graves dating from WW1, according to the local custom. However, in the majority of the mass grave sites, only the tree trunks have remained, whereas older trees can be found in Rajbrot and Brzesko.

Results

Investigations pertaining to the occurrence of phosphorus, as well as the co-occurrence of iron compounds and clay minerals in the vicinities of the nine mass graves studied, have shown a range of certain regularities.

The iron compounds that accumulate on sand grains (mainly on quartz and feldspars) contain anthropogenic phases, for instance calcium phosphates, accompanied by calcium carbonates, e.g. in Dukla, Bochnia, Niepołomice

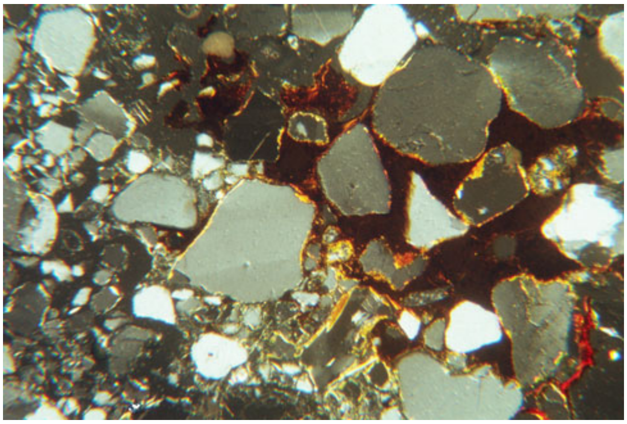

Fig. 2 A zone of sand cemented with iron compounds enriched in phosphorus. Niepołomice, close to the mass grave from WW2, at a depth of 1.22–1.26 m below the surface. Polarizing microscope, crossed polaroids, magnification ×120

and Nowy Sącz. Sandy environments favor the oxidation of organic matter and formation of various organic acids, including carboxylic, fatty, sulfonic and amino ones, followed by a drop of pH. These processes led to macerating or dissolving bone hydroxyapatite, which is indicated by the presence of P in the sediments of the grave sites (Pawlikowski 1995). The author has ascertained the absorption of anthropogenic phosphorus in mineral, poorly crystalline phases in Nowy Sącz and amorphous forms in Niepołomice (Fig. 2). Calcium phosphates were absorbed on well-crystalline iron oxyhydroxides and on clay minerals that rim grains of various minerals, for instance in Niepołomice and Rajbrot. Where iron hardpans (orsteins) formed, part of the $(OOH)^{3-}$ groups of lepidocrocite and goethite were replaced by ${PO_4}^{3-}$ anions and formed the amorphous and hydrated mineral substances identified by the author.

If decomposition takes place in a water-saturated environment, phosphides—one of the products of decomposition—hydrolyze and phosphorus is released as PH_3 and P_2H_4, with a simultaneous reduction of Fe^{3+} to Fe^{2+} (Żychowski 2009). Under these conditions, crystalline minerals containing Al and Fe change into non-crystalline mineral substances with better sorption properties. Therefore, a higher amount of iron and clay minerals in sandy sediments favors in situ preservation of decomposition products, for instance in Brzesko and Zbylitowska Góra (Fig. 3). The aforementioned significant features of sediments were observed in the burial environments studied (Table 3). The results obtained indicate certain interdependences between the development of grave site sediments and the presence of mineral iron compounds, clay minerals and anthropogenic phosphorus (Table 4), as summarized below:

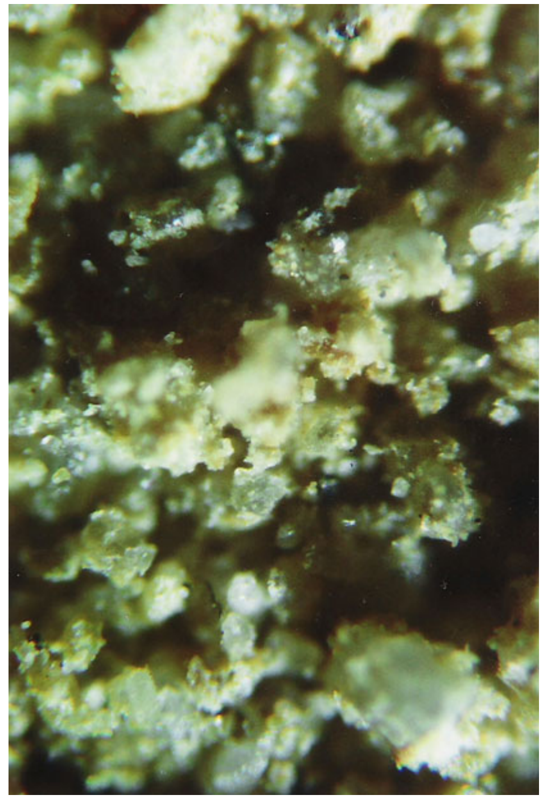

Fig. 3 Quartz grains (*white*) with clay minerals and traces of Fe–Mn compounds. Brzesko, above the mass grave from WW1, at a depth of 0.50 m. Polarizing microscope, side illumination, one polaroid, magnification ×60

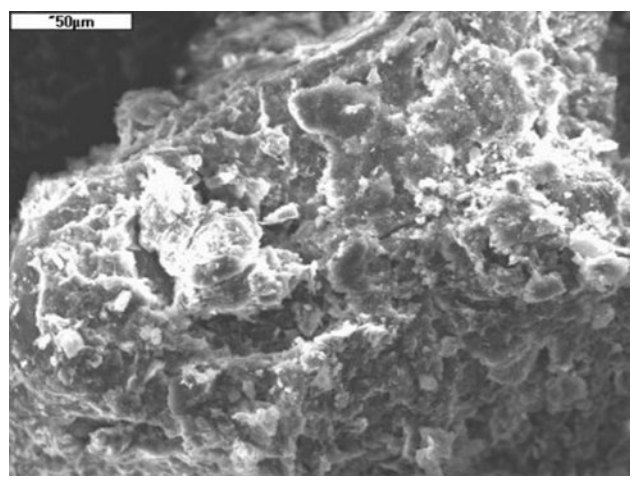

Fig. 4 Quartz grains with coatings of iron compounds that contain traces of phosphorus. Błonie, mass grave from WW1, at a depth of 1.60 m. SEM

- the amount of iron compounds enriched in anthropogenic P is higher in the more sandy horizons of the sediments, e.g., in Rajbrot;

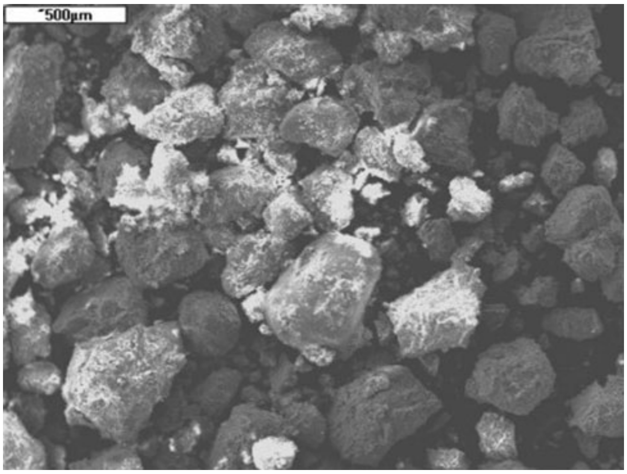

Fig. 5 Grains of quartz and aggregates of clay minerals in yellow sands with fine fragments of sandstone. Rajbrot, downslope of the mass grave from WW1, at a depth of 2.16–2.20 m, collected on 10 May 2006. SEM

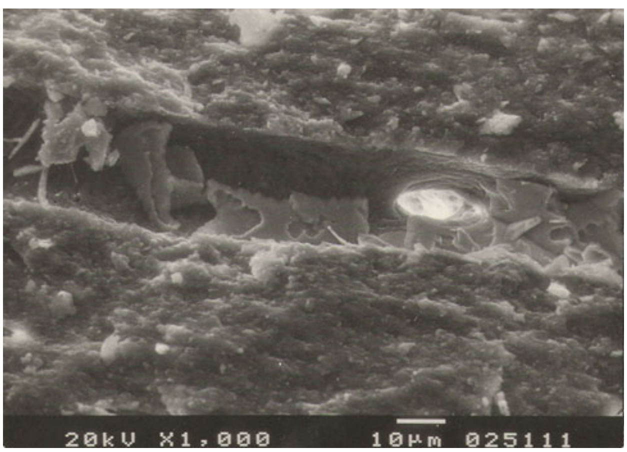

Fig. 6 A section across a microcavern in beige clays intercalated with *bluish-white* clays filled with secondary substances. Barwinek, close to the mass grave from WW2, at a depth of 1.30–1.34 m. SEM

- iron compounds in loams occur most often at the contacts of layers with different permeability, in hollows formed by rotten roots and in minor fractures, e.g., in Barwinek;
- phosphorus occurs in traceable amounts in sediments rich in clay minerals.

These regularities are most probably associated with the limited migration of water in such sediments, for instance in Bochnia, Dukla and Barwinek.

The iron compounds identified in the burial sites studied have the following features, in that they:

- often represent substances with a poorly ordered structure, e.g., in Niepołomice, Dukla, Błonie and Zbylitowska Góra;
- form microconcretions, e.g., in Rajbrot; and
- migrate easily in groundwater, e.g., in Niepołomice.

On the other hand, in more compact sediments with low permeability, containing a substantial admixture of clay minerals, the products of decomposition of human corpses usually do not migrate, e.g., in Dukla and Barwinek. Consequently, decomposition takes place in a reducing environment while carbon with its derivatives condense within burial sites as a result of oxygen being removed from organic matter. The organic slimes formed in such a process show elevated amounts of sulfur, nitrogen, etc. This type of decomposition leads to carbonification and conservation of tissue.

The results obtained show the significant dependence between the development of the sediments and the mechanism of P binding by mineral substances (Table 5). In considering other significant features of the environment (Tables 3, 4), certain regularities have been detected, as described below.

1. Sandy sediments, poorly cemented with clay minerals, localized on flat elevations, undergoing sporadic oscillations in the groundwater table and containing detrital grains with clay-ferruginous rims, represent an environment favoring the preservation of decomposition products, concentrated in the form of aggregates. Almost all such aggregates contain admixtures of anthropogenic phosphorus, e.g., in Rajbrot and Brzesko.
2. Sandy sediments characterized by frequent oscillations in the groundwater table represent an environment of fast decomposing and leaching decomposition products in the form of ions, including Ca^{2+}, CO_3^{2-}, PO_4^{3-}, OH^-, F^- and Cl^-, which are removed from the burial site, e.g., in Niepołomice (Żychowski et al. 2006a). Only on the surfaces of a few grains can the colmatage of decomposition products enriched in amorphous phosphates be seen (Żychowski et al. 2006b). Sporadically occurring clay minerals are absorption sites of decomposition products. Additionally, in the burial sites, e.g., in Błonie and Niepołomice, preserved tissue fragments can be found. The soil enriched in such organic substances shows lower absorption capacity than pure mineral sediments.
3. In the silty sediments containing an admixture of grains of other sizes, larger precipitates of phosphate substances are covered with trace amounts of secondary iron compounds. Sporadic oscillations of the groundwater table within the burial horizon favor crystallization of the phosphate substances, e.g., in Nowy Sącz.
4. In the alluvial gravels containing an admixture of clay minerals situated on a landslide-disturbed front

Table 3 Petrographical characteristic of the mass grave sediments

Locality, time of the burial	Petrography of the burial site	Characteristic features of the sediment
Niepołomice, WW2	Psammitic–aleuritic material with a variable admixture of clay minerals	Angular and weakly rounded quartz grains, fragments of Carpathian sandstones, clay minerals, hardpan horizon
Zbylitowska Góra, WW2	Water-permeated fine gravel with larger pebbles within the grave level, overlain by sediments with a variable silt–clay ratio	Fine-grained detrital material with clay minerals, quartz grains covered by clay minerals and Fe compounds, fragments of spongy bone
Brzesko, WW1	Porous sediment, weakly cemented, psammitic–aleuritic material with a variable admixture of clay minerals	The proportion between clay minerals and detrital material is highly variable
Bochnia, WW1	Aleuritic–pelitic sediment with a considerable content of the pelitic fraction (mainly minerals from the illite group)	Fragments of limestone in a loamy sediment, sandy–aleuritic sediment with organic matter
Błonie, WW1	Aleuritic–psammitic–aleuritic sediment with a variable proportion of grain fractions, quartz grains and rock fragments embedded in a clay-rich matrix	Quartz grains of various size and with variable roundness, larger grains are better rounded, all grains covered by clay minerals
Rajbrot, WW1	Loose, detrital, psammitic–aleuritic material with a variable admixture of the psephitic fraction, psammitic fraction dominates within the gravel level	Loose or weakly cemented sediments with clay minerals and iron precipitates, quartz grains covered by clay rims, carbonate grains, fragments of weathered sandstones
Dukla, WW2	Aleuritic–pelitic sediment (illite), zones mineralized by iron compounds	Zones enriched in calcium carbonate, loamy sediments
Barwinek, WW2	Aleuritic–pelitic sediment with a variable proportion of both fractions	Loamy sediments, streaks of organic matter, quartz grains within the mass of clay minerals
Nowy Sącz, WW2	Aleuritic sediment: mudstones of various types with a variable proportion of detrital grains and clay cement	Streaks of organic matter, most quartz grains are well rounded, horizons richer in psammitic fraction, remains of human tissue

of a high terrace of the Dunajec River in Zbylitowska Góra, mineralization with iron compounds is poor and these substances show poor structural ordering. This fact can be explained by the considerable variety in water conditions found at this site (swellings of mountainous rivers). These sediments do not contain secondary precipitates of anthropogenic phosphorus either. In turn, a higher concentration of phosphorus has been found in sediments with weak permeability that occur above the burial site in Zbylitowska Góra.

The sediments with a substantial content of clay minerals of the illite group, situated on scattered elevations and gently inclined slopes, are in some places richer with hydrated, secondary iron oxide–hydroxides that adsorb anthropogenic phosphorus. These compounds are mostly concentrated on streaks of organic substances, along borders between silt and clay sediments, on bone surfaces, in hollows formed by rotting roots, in fine fractures and sporadically among grains of detrital material, e.g., in Bochnia, Barwinek and Dukla.

The author has also found at the burial places various samples of plant tissue (Table 5) that were difficult to identify:

- fragments of mineralized tissue, e.g., in Niepołomice;
- organic shreds on quartz grains, e.g., in Rajbrot;
- rotted root fragments, e.g., in Dukla;
- plant microshreds, e.g., in Brzesko;
- black organic fragments, e.g., in Bochnia.

A small part of organic matter must have been mixed with sediments during the digging of mass graves. The sediments studied often reveal veins or streaks of organic substances, e.g., in Barwinek and Bochnia. The same refers to alluvia, in which a thin zone of organic precipitates may be observed, e.g., in Nowy Sącz.

Microscopic observations point to significant differences in the preservation of human tissue within sediments between the graves from WW1 and WW2. In the graves from WW1, soft tissue microfragments were observed (size from several to 15-or-so micrometers), but a more detailed determination of their origin has not been possible. Also, bones occur there occasionally as fine, poorly preserved fragments, revealing secondary mineralization of their surfaces with iron oxyhydroxides (Figs. 7, 8). These small fragments have been washed down into the sediments enclosing mass graves and are proof of a migration of decomposition products outside the grave site. Single fragments of spongy bone found in sediments have been altered,

Table 4 Forms of occurrence of iron compounds, clay minerals and phosphorus in the mass grave sediments

Locality, time of burial	Form of occurrence		
	Iron compounds	Clay minerals	Phosphorus compounds
Niepołomice, WW2	Iron-rich zone above the burial level, weak mineralization of the sediment with Fe compounds, quartz grains and rock fragments in the burial level show rims of iron oxyhydroxides whose structural ordering is weak	Quartz grains are covered in places by clay minerals	Iron compounds in the form of colmatage on some grains contain amorphous phosphates and calcium carbonate. However, many quartz and feldspar grains (including those covered by Fe compounds and clay minerals) do not contain P
Zbylitowska Góra, WW2	The sediment is weakly mineralized with iron oxyhydroxides; they show weak structural ordering; in the clay matrix there are traces of Mn compounds	Clay groundmass is enriched in Fe	No secondary precipitations of anthropogenic P in the sediment; the sediment is also enriched in Zn
Brzesko, WW1	Secondary mineralization with Fe compounds on bone tissue fragments; quartz grains are covered by clay minerals containing Fe, Mn and P	Bone tissue fragments are covered by clay minerals	Clay minerals are enriched in P
Bochnia, WW1	Fe oxyhydroxides mineralize bone surfaces; sediment is in places enriched in calcium carbonate	A considerable content of clay minerals (illite group)	Amounts of anthropogenic P close to the geochemical background
Błonie, WW1	Fe enrichment only found in the pelitic fraction; large and small grains of quartz are covered by secondary, Fe oxide-hydroxides, with a weak structural ordering; above the burial level there are thin zones of Fe oxyhydroxides	Detrital grains are covered by clay minerals	The sediments at the burial level contain traces of P (Fig. 4)
Rajbrot, WW1	Sediments are loose or weakly cemented within secondary Fe compounds (from several to approximately 15%); in the burial level there are dark brown or red-brown Fe microconcretions	Sediments are weakly cemented with clay minerals; quartz grains are covered by clay-ferruginous rims and aggregates (Fig. 5)	Clay rims on grains of all minerals contain traces of anthropogenic P (0.1%)
Dukla, WW2	Clay matrix is in places enriched in Fe compounds and calcium carbonate; the structure of Fe oxyhydroxides is weakly ordered; spaces among detrital grains are enriched in places with secondary Fe compounds	A considerable content of clay minerals (illite group)	Amounts of anthropogenic P close to the geochemical background
Barwinek, WW2	On the borders of layers with differing permeability, small amounts of secondary Fe oxyhydroxides (Fig. 6) occur in hollows and fine fractures	Loamy sediments contain concentrations with oxidized Fe compounds	P occurs together with Fe precipitates in streaks of organic matter and along the borders between silty and pelitic layers; ferruginous-organic grains are enriched in P
Nowy Sącz, WW2	Sandy horizons contain more Fe compounds enriched in P	Variable content of clay minerals	Traces of secondary, poorly crystalline phosphate substances precipitate on quartz grains

and a part of these have even turned isotropic. The bone tissue fragments observed under the microscope are mineralized to various degrees with secondary iron compounds, e.g., in Brzesko and Zbylitowska Góra. These bones have also revealed signs of penetration by aluminosilicates from the enclosing sediment. Such a situation was described by other researchers who found silicates, carbonates and manganese in the bones tested (Pawlikowski et al. 2007).

The sediments enclosing grave sites from WW2 contain fragments of soft tissue, the amount of which varies depending on the location of the burial. Most of these fragments were observed in Zbylitowska Góra in alluvial sediments covered with impermeable clays. The tissue there is considerably altered and partly mineralized by secondary Fe compounds. The bones in Nowy Sącz are better preserved. Fragments of bone tissue observed under

Table 5 Preservation of plant fragments and human tissue in the mass grave sediments

Locality, time of burial	Degree of preservation	
	Plant fragments	Human tissue fragments
Niepołomice, WW2	Fragments of mineralized plant tissue	Sporadic organic shreds, fragments of cortex bone, microfragments of bones covered by products of secondary alterations
Zbylitowska Góra, WW2	Not found	Well-preserved organic fragments of buried corpses: fragments of sponge bone, fragments of soft tissue highly altered tissue fragments partly mineralized with secondary Fe compounds
Brzesko, WW1	Microshreds	Fragments of tissue with a variable degree of mineralization with secondary Fe compounds; no bone microfragments were found (pH below 7)
Bochnia, WW1	A vein and a black fragment	Fine, isotropic fragments of a sponge bone; penetration of aluminosilicates into the bone structure; secondary mineralization of the outer part of bone with Fe oxyhydroxides (Fig. 8)
Błonie, WW1	Not found	Microfragments of soft tissue (from several to 15 or so μm), unidentifiable under the microscope
Rajbrot, WW1	Organic shreds on quartz grains	Bones are rare and poorly preserved, single fragments of altered sponge bone
Dukla, WW2	Decomposed root fragments	Fine fragments of altered sponge bone; spaces among osseous trabelculas filled with sediment
Barwinek, WW2	Sediment overgrown with mineralized mycelium, streaks of organic matter	Not found in the vicinity of the grave
Nowy Sącz, WW2	Thin zone of concentration of organic matter	Fragments of bone tissue with signs of incipient mineralization

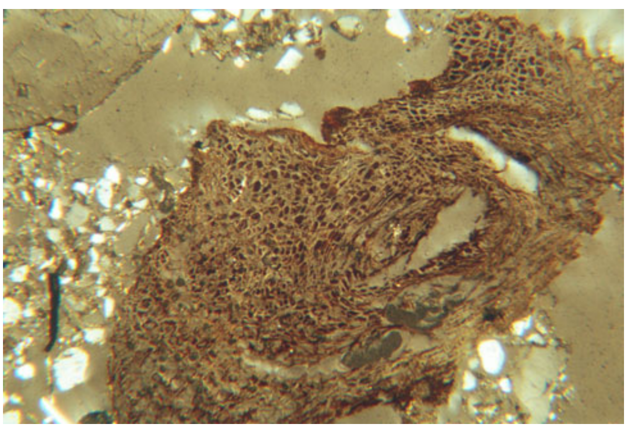

Fig. 7 A fragment of spongy bone mineralized with iron oxyhydroxides, occurring in a dark gray clay with precipitates of iron compounds. Bochnia, close to the contemporary burials, downslope of the mass grave from WW1, at a depth of 0.62–0.66 m. Polarizing microscope, crossed polaroids, magnification ×120

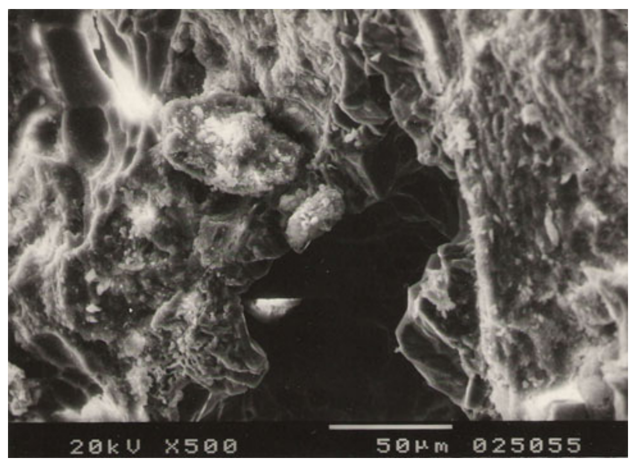

Fig. 8 A bone microfragment with signs of secondary mineralization. Bochnia, close to the contemporary burials, downslope of the mass grave from WW1, at a depth of 1.38–1.42 m. SEM

the microscope show only signs of incipient mineralization. However, in the spongy bones from Dukla, the places among osseous trabelculas have been filled with clay sediment. In Niepołomice, bone microfragments were also covered with other, microscopically unidentifiable products of these alterations. Fragments of altered cortex bone have been found close to the last mentioned grave.

Bone fragments have not been found in samples from a trench dug in the vicinity of the mass grave in Barwinek. This grave site is situated in clay-rich sediments (Table 3).

In eight of nine sampling sites, i.e., in Niepołomice, Rajbrot, Bochnia, Dukla, Nowy Sącz, Zbylitowska Góra and Brzesko, ion exchange has probably taken place between solutions from the grave subsoil and the bone matter, mineralized as a result into amorphous compounds, mostly iron oxyhydroxides.

During the sampling campaign, the author did not collect larger fragments of bones that were easily spotted. These were left where they lay in order to respect the dead and the grave sites. It is probably a reason that no secondary minerals, calcite among others, were observed precipitating on the outer or inner walls of such bones and in bone fractures. The same refers to the recrystallization of microcrystalline, biogenic hydroxyapatite into authigenic crystalline apatite.

Summary

Mineralogical and petrographical investigations were carried out in the vicinities of mass graves from WW1 and WW2. Mass graves were dug in sediments differing considerably in their development and represented silts, silty clays, silty and sandy clays, sandy silts and fine gravels. The grave sites also differ in their water conditions. In some mass graves, the groundwater table reaches periodically the burial horizon, e.g., in Niepołomice and Zbylitowska Góra, while in others it is situated below the burial horizon, e.g., in Rajbrot and Brzesko, or shows temporary increases, e.g. in Nowy Sącz. in Błonie, percolating water has flooded the mass grave situated in permeable sediments at the front of the foreland escarpment. In turn, a higher moisture content has been recorded from time to time in the remaining grave sites, i.e., in Dukla, Barwinek and Bochnia.

Psammitic and psephitic sediments (sands and gravels) with minor amounts of calcium carbonate, clay minerals and iron compounds favor the leaching of decomposition products from the immediate surroundings of mass graves. The distance of this transportation depends on the slope inclination, rain intensity and oscillation in the groundwater table. The presence of calcium carbonate, clay minerals and iron compounds results in precipitation and/or sorption of the decomposition products. Precipitation is also controlled by the pH of sediments and water. Changes in water conditions and pH values, characteristic of a temperate climate, lead to the formation of amorphous and, less frequently, weakly crystalline secondary phases, containing decomposition products. These new phases represent most often various forms of iron phosphates, e.g., ferric $FePO_4$ or weakly soluble ferrous $Fe_3(PO_4)_2$ varieties, if the respective ions ($H_2PO_4^-$, Fe^{3+} or Fe^{2+}) are present in the environment.

The sorption of most phosphorus in the form of the PO_4^{3-} ion takes place on secondary iron oxyhydroxides, as those amorphous compounds are positively charged. If left in the aeration zone above the stagnating water table, their internal structure tends to reorder. These compounds become less stable if the subsoil has been permeated with water, when the redox potential decreases and Fe^{3+} ions are reduced to Fe^{2+} ions, where various forms of P are released. Thus, in subsoil consisting of sands or gravels, absorption depends on an admixture of iron compounds and clay minerals. In contrast, circulation of water is limited in sediments rich in clay minerals and, in such cases in the immediate vicinity of burials, phosphorus occurs only in traces, being mostly bound in the immediate burial location. Migration of decomposition products in clay sediment is possible if the sediment has at least one of the following features that form water channels: fractures, intercalations of coarser-grained intercalations, openings resulting from rotten plant roots or tunnels bored by animals.

Mineralogical and petrographical investigations indicate that the processes of decomposition within mass graves followed by the leaching of decomposition products out of these sites depend first of all on the character of sediments in which the burial took place and on water conditions affected by landforms. The time that elapsed since the burial is significant in the assessment of how far decomposition processes have advanced and this refers to the preservation of both soft tissue and bones. Microfragments of human soft tissue are present in the sediments of the graves from WW2, e.g., in Niepołomice and Zbylitowska Góra. The presence of plant tissue in the form of small veins, shreds, thin zones of precipitation, etc., is widespread in most of the graves studied.

Discussion

Between the pH values 6.6 and 8.1, i.e., within the so-called recrystallization window, hydroxyapatite dissolves and recrystallizes again. Additionally, Berna et al. (Berna et al. 2004) suggest that below pH 7.5, the original bone apatite may be fully replaced by authigenic apatite. If pH values decrease below 7, the rapid dissolution of original or recrystallized hydroxyapatite starts. The presence of high amounts of calcium carbonates in sediments may slow down bone maceration, particularly in the environment of carbonate rocks, and result in secondary mineralization (Pawlikowski and Niedźwiedzki 2002). However, the sediments studied often show increased acidification around bones due to the presence of carbonic acid and organic acids, as well as methane. Acidification is explained by the formation of CO_2 when bone collagen oxidizes, followed by the reaction of the gas with water to form H_2CO_3, which then dissociates. In the water environment, at pH below 6.6, bone apatite is dissolved and both P and Ca are gradually leached from the burial site as Ca^{2+} and PO_4^{3-} ions (Żychowski et al. 2006a). A part of these ions in the first stage of the process, i.e., on leaving osseous trabeculas, crystallize in the marginal part of the bone being altered as secondary carbonates and phosphates, among which calcium phosphates prevail (Pawlikowski and Niedźwiedzki 2002). The variability of water conditions and pH of subsoil solutions were observed in the burial sites even over a 1-year time span, and it is characteristic of the climate of

Poland. Therefore, no secondary minerals have been found as a result of petrification.

Bones are stable in alkaline environments at pH values above 8.1. Such conditions were found in sandy dunes in a semi-dry steppe (Bsk according to Koppena) in the south of Australia, where calcium and hydrogen carbonate ions are dominant. As a result, secondary calcite forms in the bones found there (Pate and Hutton 1988; Pawlikowski et al. 2007). Also, hydroxyapatite transforms into vivianite-hydrated ferrous phosphate—in a reducing environment, in the presence of decomposing human remains and iron compounds, at a relatively low pH and Eh (Maritan and Mazzoli 2004). Another phosphate, authigenic mitridatite $Ca_2Fe_3^{3+}(PO_4)_3O_2{\cdot}3H_2O$, forms in waterlogged sediments in the presence of higher amounts of Ca and at higher pH and Eh values, as was observed, e.g., north of the Turkana Lake in SW Ethiopia (Rogers and Brown 1979). The issue of ion exchange has been noted by many bone researchers (Hassan et al. 1977; Parker and Toots 1980; Pate and Brown 1985; Sillen 1988). The conditions prevailing in the graves studied vary in the course of each year, which does not favor the emergence of crystalline forms of minerals.

There is an exchange of chemical substances among the minerals of the bones and some components of the surrounding sediment (Waldron et al. 1979; Nelson and Saucer 1984; Pawlikowski et al. 2007). Mechanical disintegration enhances penetration of the bones by water and accelerates chemical changes. Better soluble components are dissolved and their elements leached, whereas the weakly soluble compounds, e.g., of Fe, Al, Ti and Mn, are left behind. The ions present in soil solutions also reacts with major bone minerals that include dicalcium phosphate dihydrate (DCPD), octacalcium phosphate (OCP), amorphous calcium phosphate (ACP), tricalcium phosphate (TCP) and hydroxyapatite (HAP), of which hydroxyapatite is the most stable (Neuman 1980). The essential elements of human bones are thus phosphorus and calcium (Posner 1985) and both are leached out in the process of demineralization. On the contrary, the surfaces of hollows resulting from chemical or physical weathering (e.g. leaching or fracturing, respectively) can be mineralized with silica and iron or manganese compounds, depending on the environment (Pawlikowski et al. 2007).

My studies indicate that the form of sediments significantly affects the decomposition processes. An environment of sands and gravels with a small amount of clay minerals and Fe compounds favors the leaching of decomposition products out of burial sites. Obviously, the migration is stronger if the site is situated on a slope, within a zone of oscillating groundwater table. The sorption of phosphorus takes place if clay minerals and Fe compounds are present in sands and gravels, and migration is slowed down by fine-grained sediments (silts and pelites). Stabilization of the water table results in structural ordering of decomposition products present in the aeration zone: they crystallize and, therefore, are left within the burial site. Migration is possible only within the burial site if sediments of various types are mixed and loosened, but it almost comes to a halt if the clays surrounding the burial site are homogenous, without fractures and open channels formed by rotting roots. Undisturbed subsoil forms a barrier blocking the movement of decomposition products. The products of decomposition could be gradually released depending on human decisions. Too rapid a release of such products can, however, bring about a degradation of the environment. The cemeteries should not be sited in the areas where moisture levels are too variable, e.g., on periodically flooded areas or those with a too high groundwater table.

Conclusions

The formation and the presence of decomposition products of human remnants in the subsoil of mass graves depend mainly on the character of sediments, in which the graves were dug. The author has also established that the mechanism of binding phosphorus, the essential, characteristic element of mass burials affecting the natural environment, is significantly related to the grave subsoil and water conditions within the subsoil horizon. Water exerts a particular role, e.g., via hydrolysis. For this reason, the prolonged presence of a high groundwater table near the burial places, as well as its oscillations resulting in the periodical flooding of corpses are essential. It has been found that stabilization of decomposition products in situ is related to the presence of iron compounds and clay minerals, particularly in finer-grained, aleuritic–pelitic sediments.

The presence of secondary minerals and amorphous substances within the environment of mass graves suggests the migration of many ions. Further investigations will center on detailed identification of those ions and new chemical compounds, and also on establishing quantitative relations among them in various environments where mass graves are located. Extending the investigations to other regions with diversified geological and climatic conditions also seems necessary, as well as completing the list of possible environment types of mass graves. Distribution and migration of heavy elements derived from old weaponry, characteristic of some mass graves from WW2, is another problem put forward in this paper.

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References

Berna F, Matthews A, Weiner St (2004) Solubilities of bone mineral from archaeological sites: the recrystallization window. J Archaeol Sci 31:867–882

Dent BB, Knight MJ (1998) Cemeteries: a special kind of landfill. The context of their sustainable management, groundwater: sustainable solutions. Conference of the International Association of Hydrologists, Melbourne, February: 451–456

Dent BB, Forbes SL, Stuart BH (2004) Review of human decomposition processes in soil. Environ Geol 45(4):576–585

Forbes SL, Stuart BH, Dadour IR, Dent BB (2004) A preliminary investigation of the stages of adipocere formation. J Forensic Sci 49(3):566–574

Haslam M (2004) The decomposition of starch grains in soils: implications for archaeological residue analyses. J Archaeol Sci 31(12):1715–1734

Hassan AA, Termine JD, Haynes CV (1977) Mineralogical studies on bone apatite and their implications for radiocarbon dating. Radiocarbon 19:364–374

Higgins IJ, Burns RG (1975) The chemistry and microbiology of pollution. Academic Press, London, pp 1–256

Knight MJ, Dent BB (1995) A watery grave—the role of hydrogeology in cemetery practice. ACCA News Summer: 19–22

Mączyńska M, Pawlikowski M, Żychowski J (2006) Wyniki badań mineralogicznych i chemicznych grobu 104 i jego otoczenia. Cmentarzysko kultury wielbarskiej Babi Dół-Borcz, powiat Kartuzy. Muzeum Archeologiczne w Gdańsku. Pomorania Antiqua XXI: 249–263

Maritan L, Mazzoli C (2004) Phosphates in archeological finds: implications for environmental conditions of burial. Archaeometry 46(4):673–683

Matos BA (2001) Avaliação da ocorrência e do transporte de microrganismos no aqüífero freático do cemitério de Vila Nova Cachoeirinha, município de São Paulo, Tese (Doutorado), Instituto de Geociências, Universidade de São Paulo, São Paulo, pp 1–115

Nelson DA, Saucer NJ (1984) An evaluation of postdepositional changes in the trace element content of human bone. Am Antiq 49:141–147

Neuman WF (1980) Bone material and calcification mechanisms. In: Urist MR (ed) Fundamental and clinical bone physiology. Lippincott, Philadelphia, pp 83–107

Pacheco A, Mendes JMB, Martins T, Hassuda S, Kimmelmann AA (1991) Cemeteries: a potential risk to groundwater. Water Sci Technol 24(11):97–104

Parker RB, Toots H (1980) Trace elements in bones as paleobiological indicators. In: Behrensmeyer AK, Hill AP (eds) Fossils in the making. University of Chicago Press, Chicago, pp 197–207

Parnell JJ, Terry RE, Nelson Z (2002) Soil chemical analysis applied as an interpretive tool for ancient human activities in Piedras Negras, Guatemala. J Archaeol Sci 29:379–404

Pate FD, Brown KA (1985) The stability of bone strontium in the geochemical environment. J Hum Evol 14:483–491

Pate FD, Hutton JT (1988) The use of soil chemistry data to address post-mortem diagenesis in bone mineral. J Archaeol Sci 15:729–739

Pawlikowski M (1995) Sekrety mineralizacji tkanek. Wyd. IGSMiE PAN, Kraków, pp 1–97

Pawlikowski M, Niedźwiedzki T (2002) Mineralogia kości. Polska Akademia Nauk. Oddział w Krakowie, pp 1–111

Pawlikowski M, Koumouzelis M, Ginter B, Kozłowski JK (2000) Emerging ceramic technology in structured Aurignacian hearths at Klisoura Cave 1 in Greece. Anthr Archeol Euras 4:19–29

Pawlikowski M, Andrzejewska Al, Borowska-Strugińska B, Żądzińska El, Szperkowska K, Janowska A (2007) Mineralogiczne zmiany w strukturze kości na przykładzie badań wczesnośredniowiecznego cmentarzyska w Dobrzyniu. In: Dzieduszycki W, Wrzesiński J (eds) Środowisko pośmiertne człowieka. Funeralia Lednickie Spotkanie 9. Stowarzyszenie Naukowe Archeologów Polskich. Oddział w Poznaniu. Poznań: 303–312

Posner AS (1985) The mineral of bone. Clin Orthop Relat Res 200:87–99

Rogers RJ, Brown FH (1979) Authigenic mitridatite from the Shungura Formation, southwestern Ethiopia. Am Mineral 64:169–171

Sillen A (1988) Diagenesis of the inorganic phase of cortical bone. In: Price TD (ed) The chemistry of prehistoric human bone. School of American Research Advanced Seminar Series. Cambridge University Press, Cambridge, pp 211–299

Spongberg AL, Becks PM (2000a) Organic contamination in soils associated with cemeteries. J Soil Contam 9(2):87–97

Spongberg AL, Becks PM (2000b) Inorganic soil contamination from cemetery leachate. Water Air Soil Pollut 117:313–327

Trąbka J (2003) Thermal changes of certain heavily burnt artifacts from Chmielów Piaskowy necropoly (The Holy Cross Mountains). Polskie Towarzystwo Mineralogiczne—Prace Specjalne, Mineralogical Society of Poland-Special Papers 22(22):225–227

Waldron HA, Khera A, Walker G, Wibberley G, Green CJS (1979) Lead concentrations in bones and soil. J Archaeol Sci 6:295–298

Żychowski J (2006) Wpływ masowego grobu na zawartość wybranych związków organicznych w wodzie gruntowej. In: Ziułkiewicz M (ed) Stan i antropogeniczne zmiany jakości wód w Polsce, IV. Wyd. Uniwersytetu Łódzkiego, Łódź, pp 349–358

Żychowski J (2009) Zawartość pierwiastków w wybranych elementach środowiska przyrodniczego otoczenia masowego grobu położonego w Puszczy Niepołomickiej. Acta Scientiarum Polonorom. Formatio Circumiectus 8(3–4):41–54

Żychowski J, Lach J, Kolber M (2002) Zróżnicowanie zawartości lizyny i kwasu glutaminowego w wodach podziemnych na wybranych cmentarzach w Polsce południowo–wschodniej. In: Burchard J (ed) Stan i antropogeniczne zmiany jakości wód w Polsce, II. Wyd. Uniwersytetu Łódz-kiego, Łódź, pp 241–251

Żychowski J, Lach J, Kolber M (2006a) Wpływ podłoża z masowym pochówkiem z II wojny światowej na skład chemiczny wód gruntowych. In: Ziułkiewicz M (ed) Stan i antropogeniczne zmiany jakości wód w Polsce, IV. Wyd. Uniwersytetu Łódzkiego, Łódź, pp 349–359

Żychowski J, Pawlikowski M, Lach J (2006b) Produkty dekompozycji szczątków organicznych na przykładzie masowego grobu w Niepołomicach. Uczelniane Wydawnictwo Naukowo-Dydaktyczne. Kwartalnik AGH. Geologia 32(2):203–225